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DEVELOPMENT AND APPLICATION OF ADVANCED OPTICAL DIAGNOSTICS FOR THE STUDY OF HIGH SPEED FLOWS IN MICRO SYSTEMS

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Final Report

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2. ABSTRACT

The primary goal of this research program is the development and application of laser based flow diagnostics for the study of supersonic micro-nozzles, such as those, which might be employed for flow control and/or small satellite orbit maintenance. In this report we document the significant progress that has been made in FY-02 in the development of Molecular Tagging Velocimetry (MTV), including assessment of experimental accuracy at low ($\sim 0.10 - 3$ torr) static pressure and detailed comparisons between experimental flow field data and computational predictions using the Direct Simulation Monte Carlo (DSMC) method. Progress in the development of micro Planar Doppler Velocimetry (μ PDV) is also described.

3.1 RESEARCH HIGHLIGHTS

Introduction and Objectives

The development and application of micro devices and systems has experienced much recent growth and this trend is expected to continue for years to come. Gaseous flow through and within such devices is a principal consideration in many applications and its understanding can be crucial for optimization of performance. While the last 10 years has seen enormous progress in the general areas of Micro Electro Mechanical Systems (MEMS) design and fabrication, detailed understanding of fundamental physical flow processes on these small scales has lagged due to a lack of suitable measurement and computation tools. This program focuses on the development of quantitative velocimetry techniques for application to supersonic micro-nozzles.

The overall goal of the program is to develop and demonstrate predictive capability in two and three-dimensional, compressible free jet and wall bounded micro scale flows over a range of conditions and Mach numbers. The research focuses on addressing the following specific questions: 1) How do viscous effects quantitatively influence boundary layer growth in micro scale converging-diverging nozzles and can micro nozzles be designed to deliver supersonic flow over a wide range of stagnation conditions and Mach numbers? 2) Over what range of conditions can quantitative velocity data be obtained, and what is the practical limit of spatial resolution? 3) How is the velocity profile, in the boundary layer developed over a flat plate, affected as the flow evolves from the continuum to slip to transition regimes and can experimental measurements be used to improve computational predictions in slip and transition regimes?

Approach

Microflows are parameterized by the Knudsen number, $Kn = \lambda/\delta$, where λ is the molecular mean free path and δ is a characteristic flow length scale, which is typically a dimension of the device or system. While there are some differences in the literature, the following is a typical breakdown of how the Knudsen number delineates the possible flow regimes (Piekos and Breuer 1996): $Kn < 0.01$ (continuum flow), $0.01 < Kn < 0.1$ (slip flow), $0.1 < Kn < 3$ (transition flow), and $Kn > 3$ (free-molecule flow).

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We have focused our efforts this year on quantifying the precision and accuracy of the Molecular Tagging Velocimetry (MTV) technique, over a wide range of static conditions ($\sim 0.10 - 25$ torr). MTV is a "time-of-flight" technique in which a laser is used to "write" a line (or set of lines) into a flow by means of an optical resonance with a suitable target tracer molecule (Stier and Koochesfahani, 1999). Our measurements utilize acetone as a molecular tracer, which due to its relatively high vapor pressure at room temperature (order torr), can be readily seeded into gas phase flows. The technique utilizes the absorption of an ultraviolet photon in the range $\sim 214 - 320$ nm, and subsequent relatively long-lived radiative emission (order 0.1 - 1.0 msec). Velocity is determined by capturing an image of the displaced line a suitable time delay after excitation. The measurement requires only a single modest power pulsed near UV laser (order 5 mJ) for the tagging step, and a gatable, intensified CCD camera for the subsequent imaging (or "interrogation" step). A detailed set of measurements have been performed on the free jet flow produced by a two-dimensional, nominally Mach 2 nozzle with exit dimensions 1 mm (height) x 5 mm (span). This Mach number has been selected in order to evaluate viscous effects within a nozzle which is relatively short, but which is still convenient for providing a range of flow regimes, which extends from continuum to slip. In collaboration with the research group led by Professor Deborah Levin, of Penn State University, selected MTV data has also been directly compared to predictions from Direct Simulation Monte Carlo (DSMC) computations.

While the accuracy and spatial resolution of MTV is quite high, the technique is inherently constrained to measurements along a line or, at most, a grid of intersecting lines. Over the past several years, major progress has been made at OSU in the development of Planar Doppler Velocimetry (Clancy et al. 1999, Samimy and Wernet 2000), a spectrally resolved scattering technique which measures instantaneous, three-dimensional vector fields in a plane, by employing a narrow linewidth laser and a molecular vapor filter, which serves as a spectral discriminator. While the technique has been employed by many researchers for macro scale flows, the extension to micro flows presents a significant set of challenges. μ PDV activity has focused on proof-of concept measurements in the same Mach 2 free jet utilized for MTV measurements.

Summary of Highlights

The primary highlights of the program are as follows: i) MTV measurements in the free jet flow produced by a two-dimensional, 1 x 5 mm nominally Mach 2 nozzle, with static pressure between 0.10 and 25 torr, ii) Comparison of MTV and DSMC data at $P_0 = 10$ torr for pressure matched and under expanded flow, iii), determination of MTV precision as a function of static pressure, and iv), demonstration of μ PDV. Progress in each of these areas will be summarized below. Much more detail can be found in the Publications cited in section 4.

MTV Measurements in Mach 2 Nozzle: The optical test apparatus, fabricated during year one of the program, was employed for these measurements. The facility consists of a vertically oriented volatile vapor seeding cylinder, a 1" x 1" x 4" rectangular test cell, with four-sided optical access, a five-liter cylindrical "dump" tank, and a 1000 liter/minute vacuum pump. Test gases are delivered from standard laboratory cylinders. Nozzles are inserted into the test cell by means of standard fittings. MTV images were obtained from the flow produced by a 1 mm (height) x 5 mm (span) contoured nozzle, which was designed using the method of characteristics to produce an exit Mach number of 2, assuming inviscid

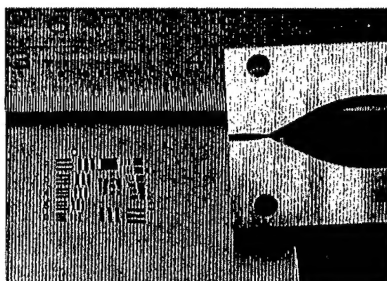


Figure 1: Photograph of 1 x 5 mm Mach 2 nozzle (scale is in inches). Flow direction is right to left.

flow. The nozzle, illustrated in Fig. 1, is fabricated using Electric Discharge Machining, based on an approach described by Bayt and Breuer (2001). By suitable combination of stagnation pressure, flow rate, and pumping speed, the nozzle can be operated in flow regimes ranging from pressure matched ($P_{\text{exit}} = P_{\text{ambient}}$) to highly underexpanded ($P_{\text{exit}} \sim 5-10 P_{\text{ambient}}$). Static pressure is measured using three Baratron pressure gauges with taps located in the nozzle plenum, in a straight section ~ 1 mm upstream of the nozzle exit, and in the flow enclosure. It was determined that the ratio of stagnation pressure to exit pressure increases rapidly as the stagnation pressure

was increased from approximately 10 to 50 torr, after which it continues to rise more slowly, leveling off to a ratio of ~ 7.1 . This corresponds, assuming isentropic flow at $T_0 = 300\text{K}$, to a Mach number of 1.94.

MTV measurements were performed for both ideally expanded ("pressure-matched") and underexpanded conditions with stagnation temperature of 300K and stagnation and flow field static pressures ranging from 10 to 150 torr and 0.10 – 25 torr, respectively. The MTV tagging laser beam was incident to the flow in a direction parallel to the height (short axis) dimension. Single lines were written on the spanwise centerline at locations ranging from $\sim 0.1\text{ mm}$ ($0.1h$) to 10 mm ($10h$) where h is the height of the nozzle, from the nozzle exit by focusing $\sim 5\text{ mJ}$ of the fourth harmonic output (at 266 nm) from a pulsed Nd:YAG "mini" laser using a 100 mm focal length plano-convex lens. Displaced images were captured using an 18 mm micro-channel plate intensified ICCD camera, employing an optical system with $\sim 4:1$ image magnification, resulting in an object plane resolution of $\sim 10 - 20$ microns and spatial scale of ~ 10 microns/pixel. Images were averaged (on the CCD) for approximately 3 - 10 seconds, at a laser repetition rate of 10 Hz, prior to read out. As will be illustrated below, quantitative velocity data is extracted from the MTV images using a simple least squares fitting procedure, similar to that which has been described in previous flow tagging studies (Lempert and Harris, 2000). The velocity is calculated from the ratio of the displacement to the elapsed time, and represents, therefore, a spatial and temporal average.

Figure 2 shows a collage of individual MTV images obtained at tagging locations varying from 0.10 to $\sim 5\text{ mm}$ (or $0.1 - \sim 5h$) downstream from the nozzle exit. In this case, the nozzle was operated near pressure matched with measured stagnation pressure of 10 torr, exit pressure of 3.16 torr, and ambient background pressure of 2.74 torr. The flow is from left to right and in all cases the time delay between tag and interrogation was 500 nsec. Qualitatively, significant curvature is seen throughout the jet profile which is an indication of significant viscous effects within the nozzle. More quantitatively, the centerline velocity is found to be an approximately constant 350 m/sec, which is over 32% lower than the expected nozzle exit velocity of $\sim 509\text{ m/s}$ for a Mach 1.94 nozzle, assuming isentropic flow. This provides additional evidence of significant viscous effects within the nozzle under these conditions. Figure 3 shows a collage of MTV images also obtained at a stagnation pressure of 10 torr, but where the nozzle was operated under highly underexpanded conditions with exit pressure of 2.87 torr, and ambient pressure of 0.40 torr. Additionally, to decrease the systematic error associated with the strong streamwise velocity gradient, the time between tag and interrogation has been reduced to 200 nsec. Note that while it is difficult to see in Fig. 3, due to the shorter time delay employed, the velocity profile near the exit is considerably more "top hat" in the underexpanded case than in the pressure matched case, indicating the presence of an inviscid "core" flow under these conditions. This shows that the magnitude of the ambient back pressure influences the flow within the nozzle, presumably due to the relatively thick, subsonic, boundary layer. The much greater expansion for the under expanded case is also apparent. Additional

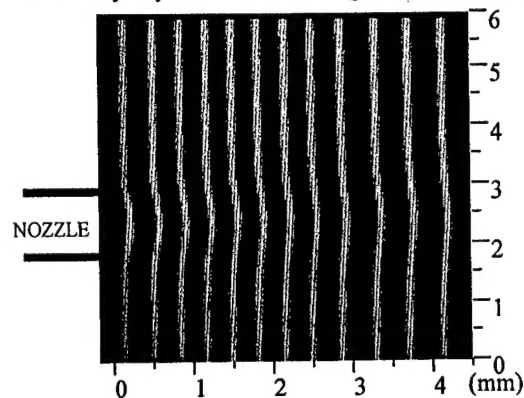


Figure 2: Collage of MTV images from 1 x 5 mm Mach 2 nozzle at $P_0 = 10$ torr. Flow is approximately pressure matched. Flow direction is left to right.

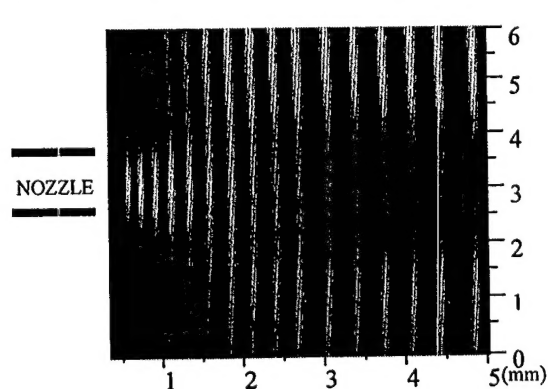


Figure 3 Collage of MTV images from 1 x 5 mm Mach 2 nozzle. Flow is highly under expanded with $P_0/P_{\text{exit}}/P_{\text{ambient}} = 10/2.87/0.40$ torr. Flow direction is left to right.

MTV image data, spanning a wide range of stagnation and static conditions, can be found in FY-02 publications 2, 4 and 5.

In a collaboration with the group led by Professor Deborah Levin of Penn State University, DSMC simulations have been performed for the cases illustrated in Figs. 2 and 3 above. Figure 4 shows false color plots of u_x , the component of velocity parallel to the principal flow axis, obtained from DSMC (upper) and from the MTV measurements (lower) corresponding to the grey scale image data of Fig. 3. It can be seen that the overall level of agreement is excellent.

The agreement between MTV and DSMC can be seen more clearly in Fig. 5, which shows vertical contours of u_x from Fig. 4 at the 1.0, 3.0, and 4.4 mm downstream locations. While the scatter is relatively high, the overall level of agreement between the data and DSMC is excellent. At the 3.0 and 4.4 h downstream positions the data does appear to be somewhat systematically low, whereas for the 1.0 mm position the data is somewhat high. It should be noted, however, that the flow field is quite dependent upon ambient pressure and these discrepancies are likely due to small (~ 0.10 torr) uncertainty in the measured wall pressure. Finally, there appears to be a discontinuity in the measured value of u_x in the downstream shear layers. The fact that this is observed on both top and bottom and at both the 3.0 and 4.4 mm locations is suggestive that the effect may be real, although it clearly also needs to be confirmed by additional experiments. Additional comparisons between MTV and DSMC can be found in the FY-02 publication 4.

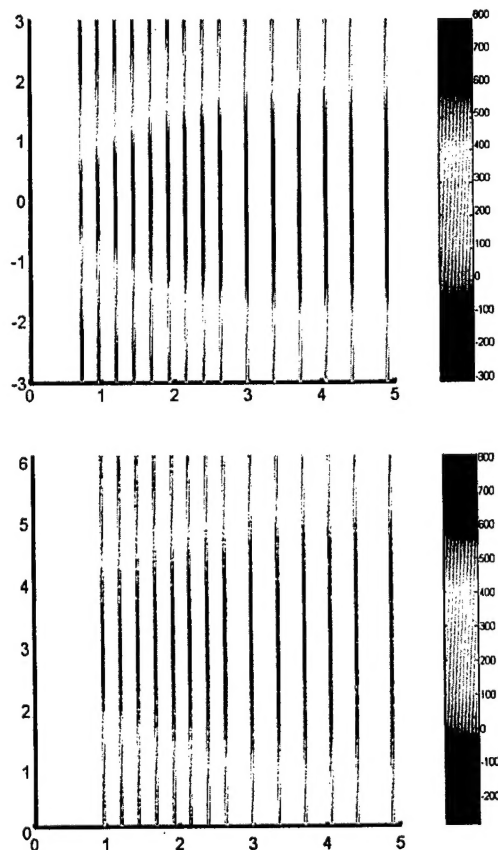


Figure 4: U_x maps for $P_0 = 10$ torr, $P_{\text{exit}} = 2.87$ torr, $P_{\text{ambient}} = 0.4$ torr (DSMC (upper) - Expt (lower)).

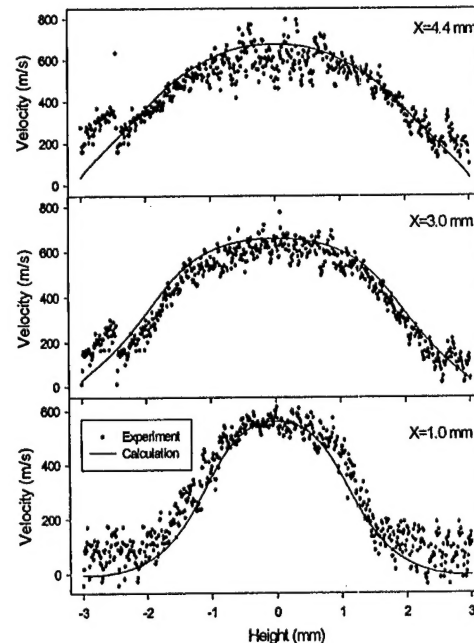


Figure 5: Comparison of experimental and DSMC horizontal velocity profiles for underexpanded flow ($P_0/P_{\text{exit}}/P_{\text{ambient}} = 10.0/2.87/0.40$ torr, respectively), at 1.0, 3.0, and 4.4 h downstream from nozzle exit.

MTV Precision Studies:

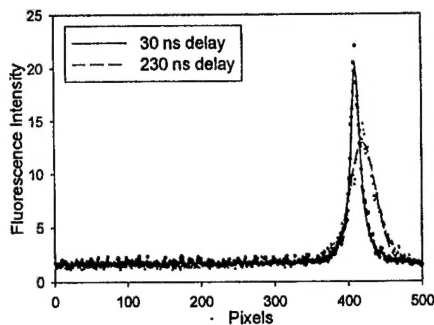


Figure 6: Single slice (right trace, dots) and least squares fit (right trace, solid curve) of grey scale intensity from representative MTV image, similar to that of Fig. 3. Left most trace is from zero delay image (not shown in Fig. 3).

Results of detailed studies of the statistical uncertainty ("precision") of the MTV technique are presented in FY-02 publications 1, 2, and 4. Figure 6 shows representative digitized grey scale pixel intensity from a single, horizontal "slice" of a typical MTV image, obtained from underexpanded flow similar to that displayed in Fig. 3 except that the ambient background pressure is 0.87 torr. Also shown in Fig. 6 are least squares fits to assumed Gaussian spatial profiles. The corresponding statistical uncertainty in velocity, returned from the fitting procedure, is ± 10 m/sec (2σ). A detailed set of similar fits have been performed as a function of static conditions. It was found that for static pressure in the range approximately 1 – 25 torr, the statistical uncertainty (2σ) in velocity is order 6 - 10 m/sec, approximately independent of flow field pressure. (FY-02 pub 1). For lower static pressures the statistical uncertainty was found to increase to order ± 20 , 50, and 70 m/sec (2σ), for 0.60, 0.30, 0.10 torr, respectively (FY-02 pub 4).

μ PDV Development: μ PDV activity this year has focused on demonstration of the technique using the same Mach 2, 1 mm x 5 mm two-dimensional nozzle employed for the MTV work. For μ PDV the nozzle was operated ideally expanded with stagnation pressure of ~ 1 bar. The actual measured Mach number, assuming isentropic expansion, was 1.97. A two camera PDV apparatus, illustrated schematically in Fig. 7, was assembled incorporating identical 5:1 image magnification for each camera. A molecular iodine cell was included in one leg to provide the filtered image. Figure 8 is a false color map of average velocity obtained in the far field of the jet (6.75 – 10 h downstream). The spatial resolution is ~ 20 microns and the measured core velocity is ~ 400 m/sec ($\sim 15\%$ higher than the ~ 360 m/sec which is predicted for an isentropic Mach 1.97 jet. Note that PDV measures the component of velocity parallel to the vector difference of the laser source propagation direction (often termed "s") and the detector observation direction (often termed "o"). For the geometry employed in these studies, this direction is 45° to the principal flow axis so that the anticipated measured velocity is $505 \cos(45)$ (or ~ 360) m/sec.

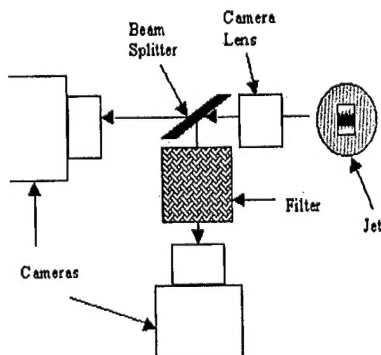


Figure 7: Schematic Diagram of μ PDV apparatus employing two cameras

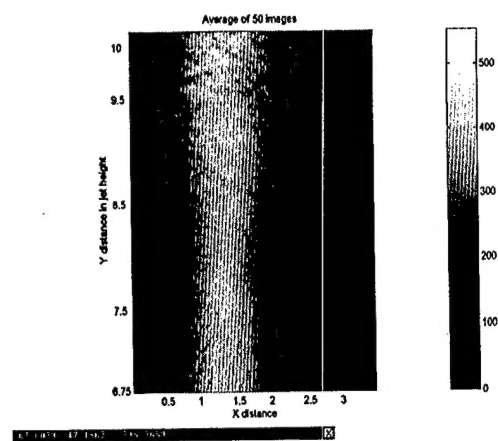


Figure 8: Proof of concept average μ PDV velocity image obtained from 1 x 5 mm Mach 2 jet.

Personnel

The co-PIs are Walter Lempert and Mo Samimy. The work has been performed, primarily, by two graduate students, Naibo Jiang and Subin Sethuram, who are both jointly advised by Professors Lempert and Samimy. Mr. Jiang has been primarily responsible for performing the MTV work and Mr. Sethuram the PDV work. Mr. Michael Boehm, a chemical engineering undergraduate, has developed the MTV image processing software. The DSMC simulations have been performed by Professor Deborah Levin and Dr. Sergey Gimelshein of Penn State University. This work has been performed at no charge to the project.

3.2 RELEVANCE/TRANSITIONS

The work described in this report is the result of a program which was initiated ~ two years ago and is still in the early stage of development. As such there have not yet been any significant transitions to federal laboratories or to industry. We are, however, as seen in the publication list below, actively disseminating the capabilities of these new diagnostics to the aerospace and micro fluidics community. It is our ultimate goal to develop diagnostic techniques which could be utilized by DoD organizations such as the Space and Missile Propulsion Division of AFRL -- Propulsion Directorate (AFRL/PRS), located at Edwards Air Force Base.

4. Publications

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2. W. R. Lempert, M. Boehm, N. Jiang, S. Gimelshein, and D. Levin, "Comparison of Molecular Tagging Velocimetry data and Direct Simulation Monte Carlo simulations in supersonic micro jet flows," Expts in Fluids **34**, pp. 403-411 (2003).
3. W. R. Lempert, N. Jiang, and M. Samimy, "Development of Molecular Tagging Velocimetry for High Speed Flows in Micro Systems, Paper AIAA-2002-0296, 40th AIAA Aerospace Sciences Meeting, Reno, NV, January 14-17, 2002.
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